



Failure analysis of cast-on-strap in lead-acid battery subjected to vibration

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ABSTRACT

Lead-acid batteries (LAB) are widely used in transportation sector for starting, lighting and ignition application. The possibility of vibration mode of failure occurs in this application due to wear and tear of the road. These vibration causes fatigue failure, particularly between the cast on strap and pillar post leading to loss of electrical connection. In this paper vibration test is conducted on a 12 V/75 Ah AGM Valve Regulated Lead-Acid Battery (VRLAB) used for above mentioned application in India. The test is carried out using Electrodynamic Vibration System model SD-10-240/GT500M/DA-10. The shaker is performed with a sinusoidal excitation, with an acceleration of 2.143G and a fixed frequency of 16.7 Hz. The peak to peak displacement is 4 mm. The deformation and crack propagation features on the surface and cross sectional area of pillar post and strap in both positive and negative group are observed with Scanning Electron Microscope (SEM). The material is yielded due to improper fusion between pillar post and strap which could not stand the vibration force. During vibration this region is vulnerable for fatigue failure.

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1. Introduction

Failure occurs when part of a component does not perform to expectation for which it is used [1–4]. It occurs due to crack formation and propagation under stress. These cracks may be initiated either by mechanical or environmental stresses. It is further activated due to heat and impurities present in the material. The study of failure analysis is to prevent its reoccurrence. Some of the factors associated with component failures are deficiency in design, fabrication, operating conditions, and improper selection of materials.

Rechargeable lead-acid batteries are widely used in automobile and electric vehicle applications [5–8,25]. In this application, vibration mode of failure is a major problem. There are many failure modes of lead-acid batteries. They vary with design, manufacturing and operating conditions [9–21]. Table 1 shows the degradation mode of failure in a lead-acid battery.

Rechargeable lead-acid battery consists of lead dioxide (PbO_2) at the positive plate and spongy metallic lead (Pb) at the negative plate. The electrolyte is sulphuric acid (H_2SO_4). During discharge, the lead and lead dioxide react with the sulphuric acid to form water and lead sulphate (PbSO_4). On charging, reverse process occurs at the respective electrodes. Based on design, lead-acid battery is divided into two types namely flooded and valve regulated. In valve regulated lead-acid battery, electrolyte is immobilized either in absorptive glassmat separator (AGM) or in the form of gel.

Vibration causes fatigue stress particularly at the joint between the cast on strap and pillar post in lead-acid battery. It leads to loss of electrical connection. There are three types of intercell connections used in lead-acid battery – 1. external, 2. through the partition and 3. up and over. In the external connectors, the pillar post and cell connector are welded together, first by welding the bush to the pillar post and then the required amount of alloy is added up to the top surface with ring mould. This connection is not suitable for VRLAB. In the case of through the partition (TTP) connectors, there will be a hole at

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Table 1

Lead-acid battery components failure characteristics.

Component	Degradation mechanism
Grid	Elevated ambient temperature overcharging, undercharging, impurities
Active material	Elevated ambient temperature, overcharging undercharging, loss of charge, excessive cycling
Separators	Elevated ambient temperature, loss of charge
Electrolyte	Impurities in electrolyte
Straps/terminals	Elevated ambient temperature, overcharging oxidation and corrosion, mechanical abuse such as vibration
Container and cover	Mechanical abuse, positive plate growth, improper cleaning agents

the walls of partition cells for squeeze welding of the pillar. This is done by resistance welding and it needs more head space. Further this type is not suitable for high rate charge/discharge applications. The up and over connectors are cast in the form of u-pieces and placed saddle wise on both sides of the intercell partition. This arrangement reduces the dead weight of the post and connector, thereby by improving battery performance at high discharge rates. In all the cases, the bonding between the pillar post and strap should have enough strength to support the vibration force. Several studies have been made to investigate the vibration based fracture of materials and components [22–25]. However, literature pertaining to the vibration mode of failure in lead-acid battery is scarce. This paper analyses the failure of cast on strap in lead-acid battery under vibration mode.

2. Assembly of test battery

The study is conducted on 12 V/75 Ah AGM valve regulated lead-acid battery with up and over connector arrangement which is normally used in automobile application. Positive and negative plates are prepared using standard grey oxide, water and sulphuric acid. The grids are made of lead–calcium–tin–aluminium alloy. Each cell is assembled by stacking five positive and six negative plates, separated by absorptive glassmat separator. Six cells of 2 V/75 Ah are assembled by connecting the cell in series. The assembled cells are added with required amount of 1.29 Sp.Gr sulphuric acid.

3. Experimental

The vibration test is carried out on the assembled battery both in horizontal and vertical directions using Spectral dynamics Electrodynamic Vibration System SD-2200-9/DA-10 as shown in Fig. 1. The shaker is performed with a sinusoidal excitation, having an acceleration of RMS (root-mean-square) 2.143G and a fixed frequency of 16.7 Hz. The peak to peak displacement is 4 mm (constant). The velocity is 0.210 m/s. The Fig. 2 shows the sine response spectrum graph of the system. Before subjecting the battery for vibration, it is cycled at 20 h rate with a constant current of 3.75 A. The capacity values are shown in Fig. 3. The cycling test is conducted, with a Bitrode battery LCN tester, interfaced to a data acquisition system. In the horizontal position the battery operates in *x* and *y* directions, with the terminals positioned in line with respect to the direction of travel in *x* direction and perpendicular to the direction of travel in *y* direction. The battery is vibrated for 8 h in three directions. The test is terminated when the battery terminal voltage 12 V attains to zero.

4. Destructive examination of test batteries

The battery is destructively examined, by removing the battery lid as shown in Fig. 4a. The failed components and related features of the battery are shown in Fig. 4b–d. The deformation and crack propagation features on the surface and cross sectional area of pillar post and strap are observed using JEOL Scanning Electron Microscope (SEM). It is seen that the failure is



Fig. 1. View of the Electrodynamic Vibration System – battery under test.

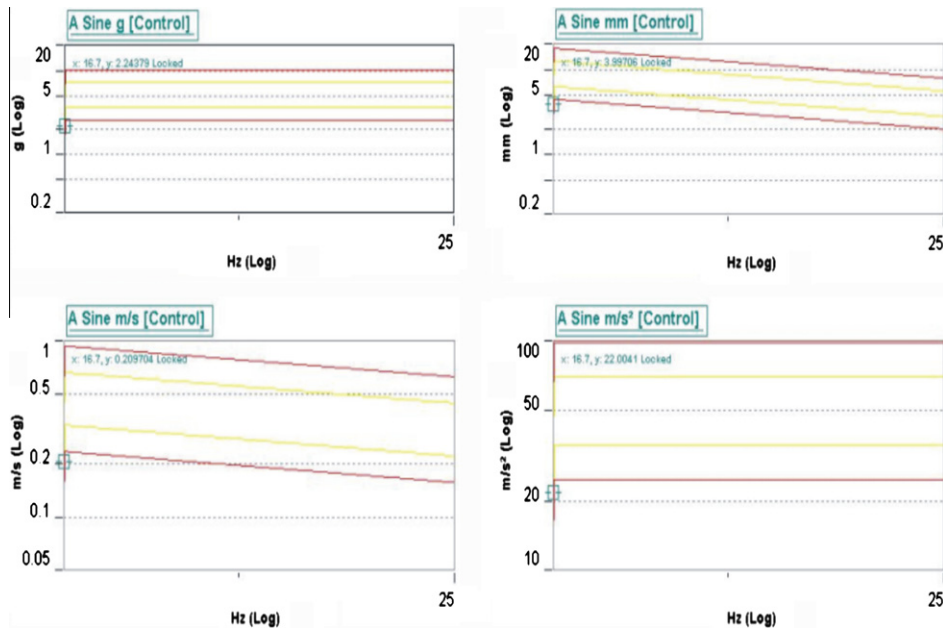


Fig. 2. Sine response spectrum.

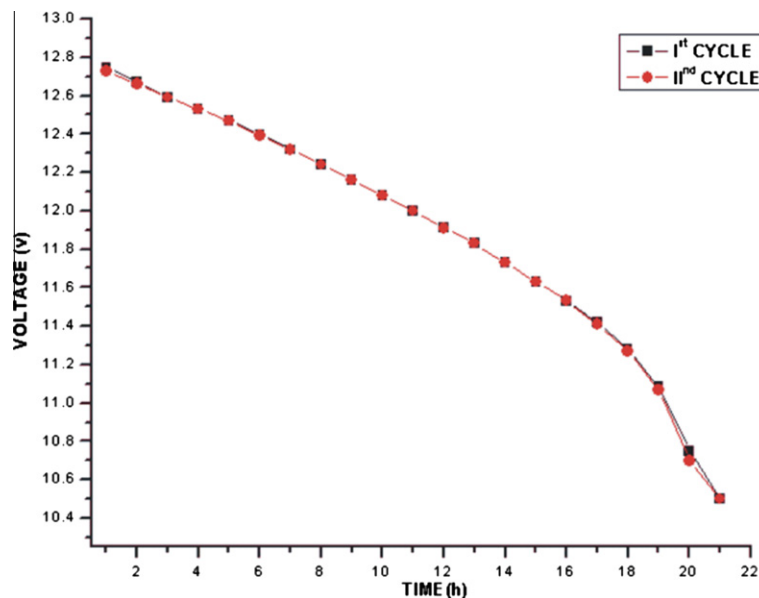


Fig. 3. Shows the performance of VRLAB before vibration test.

initiated at the contact region between the pillar posts and cast on strap (COS). The cracked COS and pillar post are removed from the cells for microscopic examination. Care is taken to prevent alteration of the microstructure due to thermal degradation of residues and also by way of introduction of contaminants. Table 2 gives individual cell voltage of the battery after the vibration test.

4.1. Visual inspection

The schematic diagrams of COS and pillar post are shown in Fig. 5a and b and 6a and b respectively. The lead alloy running over the top of the grouped battery plates in a cell is connected to the pillar post. This pillar post extends over the partition between cells and strap connects the cells in series. Each cell is of two volts. For a 12 V battery there are six cells connected in series.

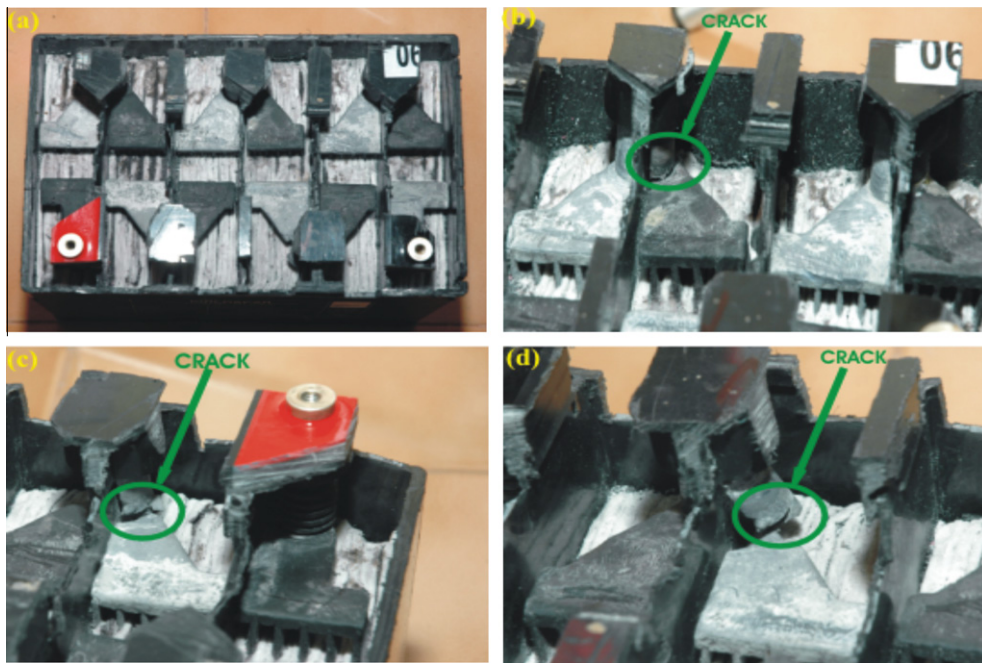


Fig. 4. A 12 V/75 Ah six cell monobloc with lid removed.

Table 2

Shows the cell and battery voltage after vibration test.

Cell no.	Individual cell voltage
01	2.095
02	2.104
03	2.100
04	2.102
05	2.101
06	2.107
Battery voltage = 0	

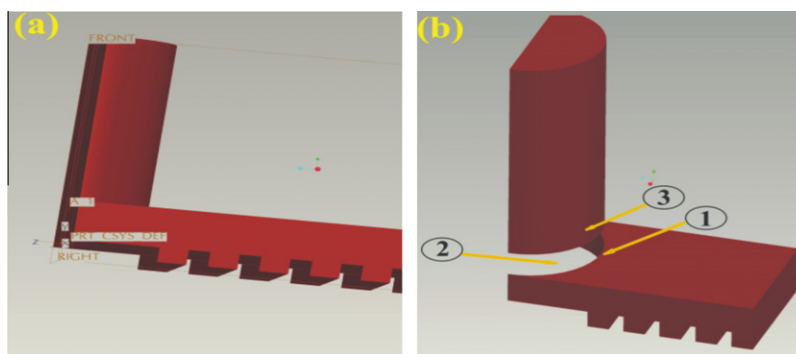


Fig. 5. 3D view of COS assembly. (1). Surface of strap, (2). Cross section of strap, (3). Surface of pillar.

5. Results and discussion

5.1. Macroscopic investigation

The macroscopic appearance of the fracture in the respective elements are shown in Figs. 7 and 8a–d. Visual inspection shows the propagation of crack between COS and pillar post.

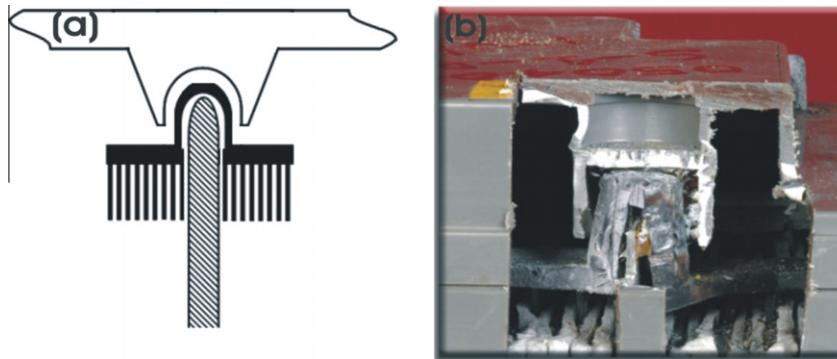


Fig. 6. Schematic and photographic view of intercell connector.

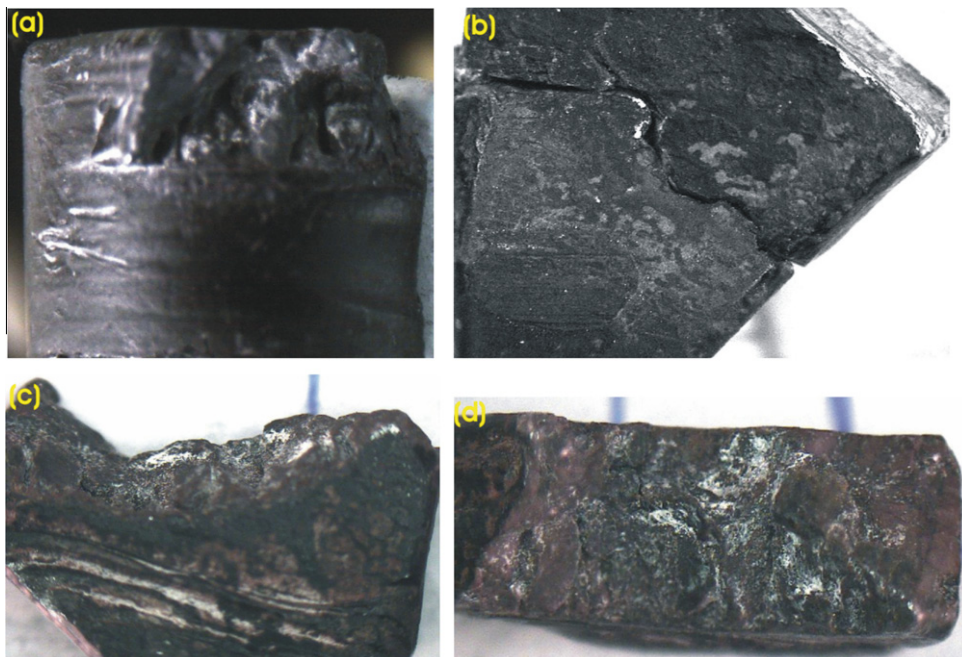


Fig. 7. (a) Surface of the damaged positive pillar post, (b) rotated view macroscopic images of a match between positive pillar post and COS, (c and d) samples of the surface and cross section of cast on strap.

5.2. Fractography

5.2.1. Fractographic investigation of surface of negative strap

When the battery is subjected to vibration crack occurs at the interface of mechanical joints. Fig. 9a shows how the pillar post attached portion of material is removed from the strap. The same location is shown at higher magnification in Fig. 9b–d. The edges of the microstructures are lined with fine beads and short threads. A thin electrolyte film on the cracked surface initiates the electrochemical reaction. Lead at the cracked surface becomes lead sulphate. This conversion of lead to lead sulphate leads to volume expansion which imposes stress on the pillar post. Thus the pillar post is unable to withstand the generated force, leading to crack initiation and propagation.

5.2.2. Fractographic investigation of negative strap cross section

Fig. 10a–d clearly indicates how the pillar post is torn off from the cast on strap. The broad irregular region demonstrates the wear on the surface. The Fig. 10b shows a short thread which indicates the ductile mode of failure. The cast on strap is made of lead–calcium–tin–aluminium alloy and pillar post is lead–tin alloy. These alloys are highly ductile. It appears that the contact between the surface is either incomplete, or the mating surface temperature does not promote good fusion between cast on strap and pillar post. In either case, it results in incomplete fused joint. This led to crack propagation.

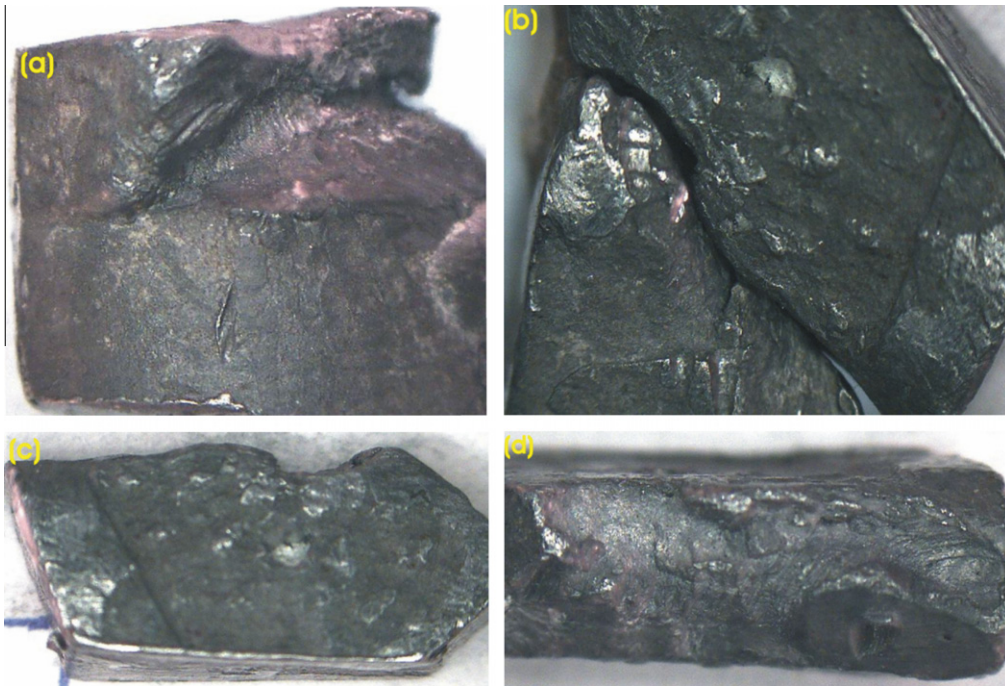


Fig. 8. (a) Surface of the damaged negative pillar post, (b) rotated view macroscopic images of a match between negative pillar post and COS, (c and d) Samples of the surface and cross section damaged cast on strap.

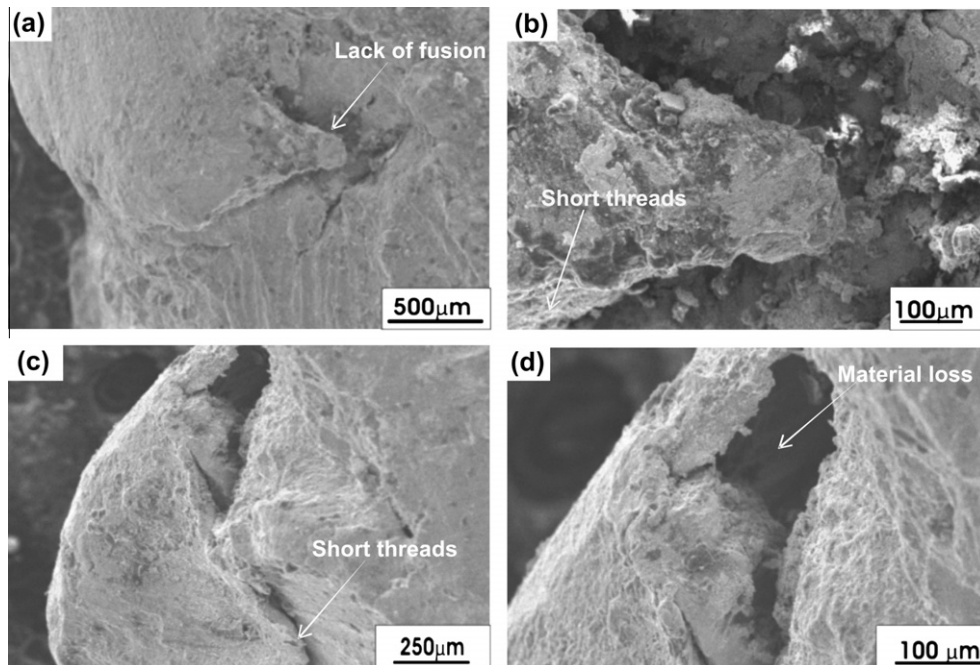


Fig. 9. SEM images of vibration deformation structures: surface of negative straps.

5.2.3. Fractographic investigation of surface of negative pillar post

Fig. 11a and b shows the fractured surface of the negative pillar post attached to the negative strap. The surface is severely suffered due to rubbing action between the pillar post and strap. This leads to crack propagation in lead alloy. Lead sulphate

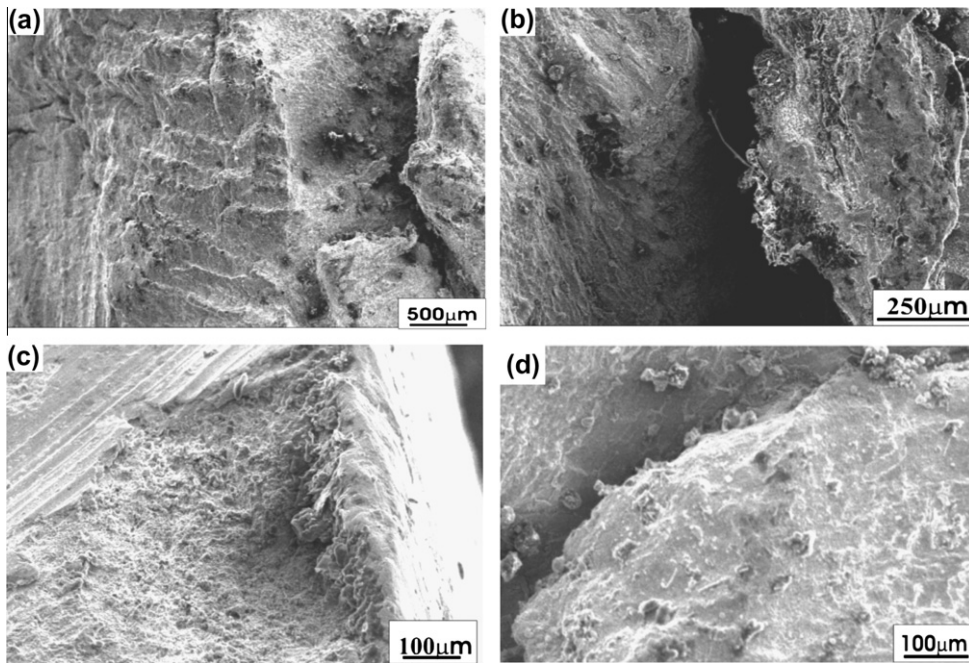


Fig. 10. SEM images of vibration deformation structures: cross section of negative straps.

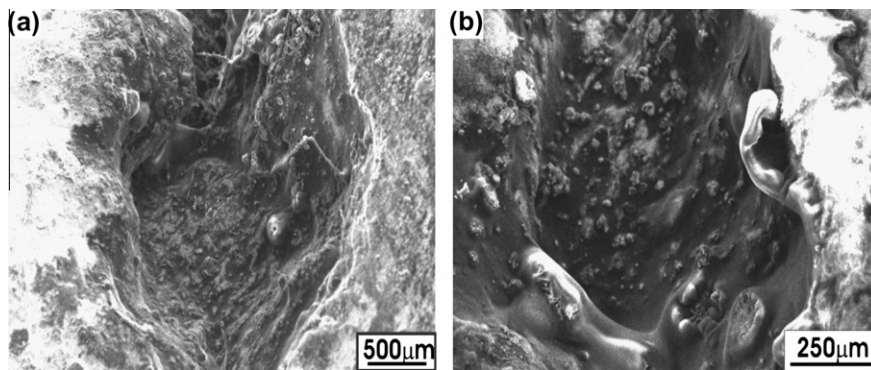


Fig. 11. SEM images of vibration deformation structures: surface of negative pillar.

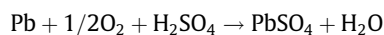
is formed at the edges of the grain boundaries. When the alloy is stressed in tension, localized electrochemical dissolution of metal occurs. This combined with localized plastic deformation accelerate the growth of the crack.

5.2.4. Fractographic investigation of surface of positive strap

Fig. 12a–d shows the surface of the failed location of positive cast on strap (COS). Since the material is attacked by sulphuric acid, a lot of corrosion products are seen. The microscopic examination shows the crack occurred by fatigue failure.

5.2.5. Fractographic investigation of positive strap cross section

The examination of fractured surface of positive strap is shown in Fig. 13a–e. It is clearly of crazed type. Through this crazing sulphuric acid is penetrated. The fractured surface shows heavily oxidized and corroded surface. This is attributed to oxygen reduction reaction involving the reduction of oxygen gas produced at the positive plate on a lead strap leading to lead sulphate and water formation. The reaction is given below



Thus the converted lead sulphate (PbSO_4) in the lead strap cannot be returned back to lead (Pb).

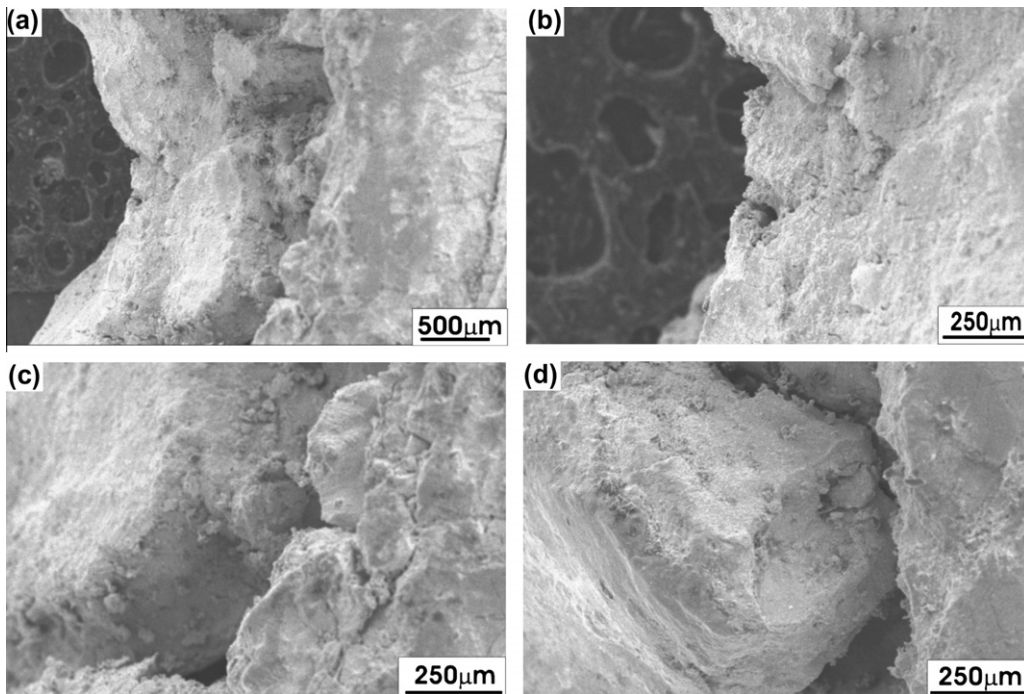


Fig. 12. SEM images of vibration deformation structures: surface of positive straps.

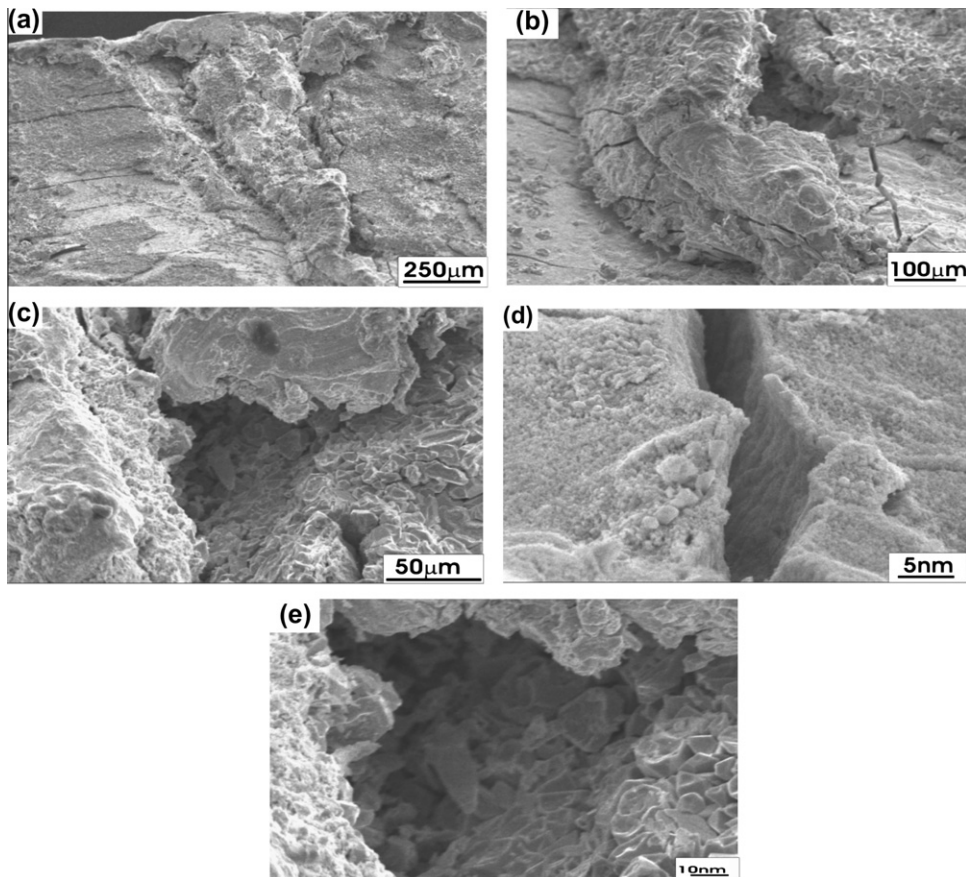


Fig. 13. SEM images of vibration deformation structures: cross section of positive straps.

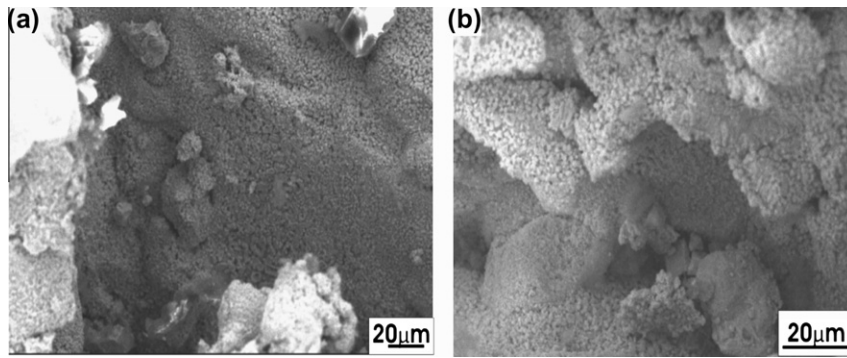


Fig. 14. SEM images of vibration deformation structures: surface of positive pillar.

5.2.6. Fractographic investigation of surface of positive pillar post

Fig. 14a and b shows the fractured surface of the positive pillar post attached to the strap. It is seen that the surfaces are attacked with sulphuric acid and a lot of corrosion products are seen. As the alloy has lower tin content the rate of corrosion is increased [27]. Selection of alloy and its composition are of crucial requirements for strap alloy in lead-acid battery [26–32]. Tin is added to provide better fusion and increased weld integrity. Further it contributes to the desirable mechanical properties and improves the corrosion characteristics of the alloy. Its addition also lowers the electrical resistance of the alloy and improves strap bonding characteristics.

6. Conclusion

In this study the experiment is carried out to investigate how the crack is initiated at the cast-on-strap and pillar post of AGM valve regulated lead-acid battery. The microscopic inspection confirmed that the failure is due to insufficient penetration of molten metal at the joint. Addition of more than 2%wt tin content will increase the amount of eutectic liquid and improves the fluidity of the alloy. Further lowering solidification rate increases bonding between cast-on-strap and pillar post.

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